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Measurement of the Lifetime of the B_s^0 Meson from $D_{\bar{s}}\ell+$ Correlations

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Measurement of the Lifetime of the B_S^0 Meson from $D_S^- \ell^+$ Correlations

The CDF Collaboration[1]

Abstract

The lifetime of the B_S^0 meson is measured using the semileptonic decay $B_S^0 \to D_S^- \ell^+ \nu X$. The data sample consists of approximately 110 pb^{-1} of $p\bar{p}$ collisions at $\sqrt{s} = 1.8$ TeV collected by the CDF detector at the Fermilab Tevatron collider. There are 254 ± 21 $D_S^- \ell^+$ signal events where the D_S^- is reconstructed through its decay mode $D_S^- \to \phi\pi^-$, $\phi \to K^+K^-$. Using these events, the B_S^0 meson lifetime is determined to be $\tau(B_S^0) = 1.37\ ^{+0.14}_{-0.12}$ (stat.) $\pm$ 0.04 (syst.) ps. The B_S^0 meson proper decay length distribution has been examined for a lifetime difference between the two CP eigenstates of the B_S^0 meson, B_S^H and B_S^L.

1 Introduction

The lifetime differences between the bottom hadrons can probe the B-decay mechanisms which are beyond the simple quark spectator model. In the case of charm mesons, such differences have been observed to be quite large ($\tau(D^+)/\tau(D^0) \sim 2.5$). Among bottom

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hadrons, the lifetime differences are expected to be smaller due to the heavier bottom quark mass. Phenomenological models predict a $\simeq 5\%$ difference between the B^+ and B^0 meson lifetimes and very similar B^0 and B_S^0 lifetimes [1]. This is consistent with the previous measurements of B^0/B^+ meson lifetime, as well as recent B_S^0 lifetime measurements [2].

The two mass eigenstates of the B_S^0 meson, B_S^H and B_S^L (L = 'light', H = 'heavy') are related to the flavour eigenstates by

$$|B_S^L\rangle = p|B_S^0\rangle + q|\overline{B}_S^0\rangle \text{ and } |B_S^H\rangle = p|B_S^0\rangle - q|\overline{B}_S^0\rangle. \tag{1}$$

We further define

$$\Delta m = m_H - m_L,\ \Delta, \ = ,_H - ,_L, \text{ and } , \ = \frac{,_H + ,_L}{2}. \tag{2}$$

where $m_{L,H}$ and $,_{L,H}$ denote the mass and decay width of B_S^L and B_S^H. In the CKM Model the ratio $\Delta m/\Delta,$ depends only on QCD corrections [3]. Thus a measurement of $\Delta,$ would imply a determination of Δm and a way to infer the mixing parameter x_S of the B_S^0 meson, as well as a measurement of the ratio of CKM matrix elements $|V_{td}|/|V_{ts}|$. Theoretical predictions could expect a value for $\Delta,$ as large as 30% [4].

Since the decay $B_S^0 \to D_S^- \ell^+ \nu X$[2] is expected to be an equal mixture of B_S^L and B_S^H, one way to measure $\Delta,$ is to describe the proper lifetime distribution from $D_S^- \ell^+$ correlations by a functional form of

$$\mathrm{e}^{-(\Gamma + \frac{\Delta\Gamma}{2})t} + \mathrm{e}^{-(\Gamma - \frac{\Delta\Gamma}{2})t}. \tag{3}$$

In this paper, we first present an updated measurement of the B_S^0 lifetime using the semileptonic decay $B_S^0 \to D_S^- \ell^+ \nu X$, where the D_S^- is identified via $D_S^- \to \phi\pi^-$, $\phi \to K^+K^-$. The data sample for this paper consists of approximately 110 pb^{-1} of $p\overline{p}$ collisions at $\sqrt{s}$=1.8 TeV collected by the CDF detector during the 1992-1995 run. We then examine the decay time distribution for a lifetime difference between the B_S^H and B_S^L.

[2] Throughout the paper references to a specific charge state imply the charge-conjugate state as well.

2 The CDF Detector

The CDF detector is described in detail elsewhere [5]. We describe here only the detector features most relevant to this analysis. Two devices inside the 1.4 T solenoid are used for the tracking of charged particles: the silicon vertex detector (SVX) and the central tracking chamber (CTC). The SVX consists of four layers of silicon microstrip detectors and provides spatial measurements in the r-φ plane. At CDF, φ is the azimuthal angle, θ is the polar angle measured from the proton direction, and r is the radius from the beam axis (z-axis). CTC and SVX give a track impact parameter resolution of about $(13 + 40/p_T)$ μm [6], where p_T is the transverse momentum of the track in GeV/c. The transverse profile of the beam is circular and has an RMS of $\sim$ 35 μm, while the longitudinal beam size is $\sim$ 30 cm. The CTC is a cylindrical drift chamber containing 84 layers grouped into 8 alternating superlayers of axial and stereo wires. It covers the pseudorapidity interval $|\eta| < 1.1$, where $\eta = -\ln[\tan(\theta/2)]$. Outside the solenoid are electromagnetic (CEM) and hadronic (CHA) calorimeters ($|\eta| < 1.1$) that employ a projective tower geometry. A layer of proportional wire chambers (CES) is located near shower maximum in the CEM and provides a measurement of electromagnetic shower profiles in both the φ and z directions. Two muon subsystems in the central region are used, the central muon chambers (CMU) and the central upgrade muon chambers (CMP), with total coverage of 80% for $|\eta| \leq 0.6$. The CMP chambers are located behind 8 interaction lengths of material.

3 Data Selection

Events containing semileptonic B_s^0 decays were collected using inclusive electron and muon triggers. The E_T threshold for the principal single electron trigger was 8 GeV, where $E_T \equiv E \sin\theta$ and E is the electromagnetic energy measured in the calorimeter. The single muon trigger required a $p_T > 7.5$ GeV/c track in the CTC with matched track segments in both the CMU and CMP systems. Offline identification of an electron and muon is described in references [7] and [8].

The $D_S^- \to \phi\pi^-$ reconstruction started with a search for ϕ candidates. We first defined a search cone around the lepton candidate with a radius $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\varphi)^2}$ of 0.8. Any two oppositely charged tracks with $p_T > 1.2$ GeV/c within that cone were assigned kaon masses and combined to form a ϕ candidate. No kaon identification was used in the ϕ selection. Each ϕ candidate was required to have a mass within ± 10 MeV/c^2 of the world average ϕ mass [9]. The ϕ candidate was then combined with another track of $p_T > 0.8$ GeV/c inside the cone which had the opposite charge of the lepton (the 'right-sign' combination). This third track was assigned the pion mass. To ensure a good decay vertex measurement, track quality cuts were imposed on the lepton and the three track candidates forming the D_S^- candidate. The K^+, K^-, and π^- tracks were then refit with a common vertex constraint. The confidence level of that fit was required to be greater than 1%. Since the ϕ has spin 1 and both the D_S^- and π^- are spin 0, the helicity angle Ψ, which is the angle between the K^+ and D_S^- directions in the ϕ rest frame exhibits a distribution $dN/d(\cos\Psi) \sim \cos^2\Psi$. A cut $|\cos\Psi| > 0.4$ was therefore applied to suppress the combinatorial background, which we found to be flat in $\cos\Psi$ distribution. The mass of the $D_S^-\ell^+$ system was required to be between 3.0 and 5.7 GeV/c^2 in order to be consistent with coming from a B_S^0 decay. We also applied an isolation cut $E_T^{\text{iso}}/p_T(\phi\pi^-) < 1.0$ on the D_S^- candidate, where E_T^{iso} is a sum of transverse energy within a cone of radius 0.4 in η-φ space around the lepton candidate, excluding the lepton energy. This cut eliminated many of the fake D_S^- combinations from high track multiplicity jets. Furthermore, we required that the reconstructed D_S^- decay vertex be positively displaced from the primary vertex along the direction of the $D_S^-\ell^+$ momentum. Finally, we required that the D_S^- candidates have a proper decay length of less than 0.1 cm. This requirement removed those events with very long-lived D_S^- candidates, where the long extrapolation back to the B_S^0 decay vertex resulted in a poor vertex measurement. Figure 1 shows the $\phi\pi^-$ invariant mass distribution for the 'right-sign' $D_S^-\ell^+$ combinations. A D_S^- signal with mean of 1.967 GeV/c^2 and width of 9.2 MeV/c^2 is observed. Evidence of the Cabibbo suppressed $D^- \to \phi\pi^-$ decay is also present. The shaded distribution shows the 'wrong-sign' combinations, and no enhancement is seen.

We select a signal sample using a D_S^- mass window of 1.946 to 1.988 GeV/c^2. A total of 395 events are found with a background fraction f_{bg} of 0.36 ± 0.05. The number of $D_S^- \ell^+$ events above background in the sample is 254 $\pm$ 21.

4 B_S^0 Lifetime Analysis

There are two possible sources of non-strange B meson decays which can lead to right-sign $D_S^- \ell^+$ combinations. The first process is $\overline{B}^0/B^- \to D_S^- DX, D \to \ell^+ \nu X$, where D is any charmed meson. This decay produces softer and less isolated leptons than that from B_S^0 semileptonic decay and therefore the acceptance for this source relative to the signal is quite small ($< 1\%$). Using the BR($B \to D_S X$) [9] and the semileptonic branching ratios of D^0 and D^+ [9], we estimate the fraction of this type of background is less than 1%. The second process is a four body decay $B^0/B^+ \to D_S^- \mathbf{K} \ell^+ \nu$, where $\mathbf{K}$ denotes any type of strange meson. Because of the low probability of producing $s\overline{s}$ pairs and the limited phase space, this process is suppressed and has not been observed experimentally [10]. Based on the theoretical limit $\mathrm{BR}(B^0/B^+ \to D_S^- \mathbf{K} \ell^+ \nu) \leq 0.025 \cdot \mathrm{BR}(B^0 \to \ell^+ \nu X)$ [11] and detection efficiency, we expect less than 2.6% of our $D_S^- \ell^+$ combinations from this source. We have also considered the background from $B_S^0 \to D_S^- D_S^+$ decays, with one D_S decaying semi-leptonically. Monte Carlo studies predict the background fraction from this source to be $< 1\%$. In summary, the contribution of all above physics backgrounds is quite small compared to the combinatorial background. We account for contributions from $\overline{B}^0/B^- \to D_S^- DX$ and $B_S^0 \to D_S^- D_S^+$ decays in our lifetime fit, and treat the contribution of $B^0/B^+ \to D_S^- \mathbf{K} \ell^+ \nu$ decays as a source of systematic uncertainty for the B_S^0 lifetime measurement.

The secondary vertex where the B_S^0 decays to a lepton and a D_S^- (referred to as V_{B_S}) is obtained by intersecting the trajectory of the lepton track with the flight path of the D_S^- candidate. The transverse decay length L_{xy} is defined as the displacement in the transverse plane of V_{B_S} from the primary vertex. The effect of the unknown B_S^0 relativistic boost is partially removed event-by-event with the factor $p_T(D_S^- \ell^+)/M(B_S^0)$ (where $M(B_S^0) = 5.37$ GeV/c^2) and leads to a corrected decay length $\xi = L_{xy} M(B_S^0)/p_T(D_S^- \ell^+)$ which is referred to as the 'proper decay length'. A residual correction between $p_T(D_S^- \ell^+)$ and $p_T(B_S^0)$ is done statistically by convoluting a Monte Carlo distribution of the p_T correction factor K= $p_T(D_S^- \ell^+)/p_T(B_S^0)$ with an exponential decay distribution in the lifetime fit. The K distribution has an average value of 0.86 and an RMS of 0.10 and is approximately constant as a function of $p_T(D_S^- \ell^+)$. To model the proper decay length distribution of the background events contained in the signal sample, we define a background sample which consists of the right-sign events from the D_S^- sidebands (1.885-1.933 and 2.001-2.050 GeV/c^2) and the wrong-sign events from the interval 1.885-2.050 GeV/c^2.

The proper decay length distribution (Figure 2) is fit using an unbinned maximum log-likelihood method. Both the B_S^0 lifetime and the background shape are determined in a simultaneous fit using the signal and background samples. Thus the likelihood function $\mathcal{L}$ is a combination of two parts: $\mathcal{L} = \prod_i^{N_S}[(1 - f_{bg})\mathcal{F}^i_{Sig} + f_{bg}\mathcal{F}^i_{bg}] \cdot \prod_j^{N_B} \mathcal{F}^j_{bg}$, where N_S and N_B are the number of events in the signal and background samples. The signal probability function $\mathcal{F}_{Sig}$ consists of a normalized decay exponential function (defined for only positive decay lengths and symbolized by $\mathcal{E}_+$) convoluted with the K distribution and a Gaussian resolution function $\mathcal{G}$: $\mathcal{F}^i_{Sig}(c\tau, \mathbf{s}) = \mathcal{E}_+(-Kx, c\tau) \otimes K^{dist} \otimes \mathcal{G}(\xi^i - x, \mathbf{s}\sigma^i)$, where ξ^i is the measured proper decay length with uncertainty σ^i (typically $\sim 100\mu$m) and x is the true proper decay length. The scale factor $\mathbf{s}$ accounts for the underestimation of the decay length error. The background is parameterized by a Gaussian centered at zero, and separate positive and negative exponential tails. The best fit values of $c\tau$ and s are found to be $412 \, ^{+\,42}_{-\,37}$ μm and 1.33 $\pm$ 0.06 respectively. Figure 2a) shows the proper decay length distribution of the signal sample with the result of the fit superimposed. The shaded curve shows the sum of the background probability function over the events in the signal sample. The same distribution of the background sample is shown in Figure 2b) with the result of the fit superimposed. As a consistency check, we also fit the D_S^- lifetime from the proper decay length measured from the tertiary vertex V_{D_S} to the secondary vertex V_{B_S}. Since the D_S^- decay is fully reconstructed, its relativistic boost is known and a convolution with a p_T correction factor distribution in the fit does not apply. The result is $c\tau(D_S^-) = 134\,^{+18}_{-15}\ \mu m$, which is consistent with the world average value [9]. Figures 3a) and 3b) show the D_S^- proper decay length distributions for the signal and background samples, respectively, with the results of the fit superimposed.

Table 1 lists all sources of systematic uncertainty considered in this analysis. The major contribution comes from the background shape. To model the contribution to the signal from the combinatorial backgrounds, we combined the events from both right-sign and wrong-sign sideband regions. We find a $\pm$ 11 μm variation in the lifetime when using each sideband region individually.

Quoting the statistical and systematic uncertainties separately, we measure the B_S^0 lifetime using semileptonic decays to be $\tau(B_S^0) = 1.37\,^{+0.14}_{-0.12}$ (stat.) ± 0.04 (syst.) ps. This result is consistent with the world average of $1.55\,^{+0.11}_{-0.10}$ ps [2].

In an attempt to fit the B_S^0 proper decay length distribution for two lifetime components, we try to fit our signal to a function of the form $e^{-(c\tau+\Delta c\tau/2)^{-1}} + e^{-(c\tau-\Delta c\tau/2)^{-1}}$ where $c\tau$ is fixed to the value found in fitting the sample for a single lifetime. We find $\Delta c\tau = 205\,^{+127}_{-205}\ \mu$m and conclude that we have no sensitivity to determine a lifetime difference with the statistics of our current data sample.

5 Conclusion

In conclusion, we have presented an updated measurement of the B_S^0 lifetime using semileptonic decays. This measurement is consistent with the previous CDF measurement and with the curent world average. We have searched for a lifetime difference between the two CP eigenstates of the B_S^0 but find no sensitivity with the statistics of the current sample.

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Research Council of Canada; the National Science Council of the Republic of China; and the A. P. Sloan Foundation.

Table 1: Semileptonic mode systematic uncertainties.

Error Source	$\sigma_{c\tau}(B_S^0)$ (μm)
Background Shape	± 11
Selection Bias	± 4
Trigger Turn-on	± 3
Error Scale	± 4
Physics Backgrounds	± 3
Total	± 13

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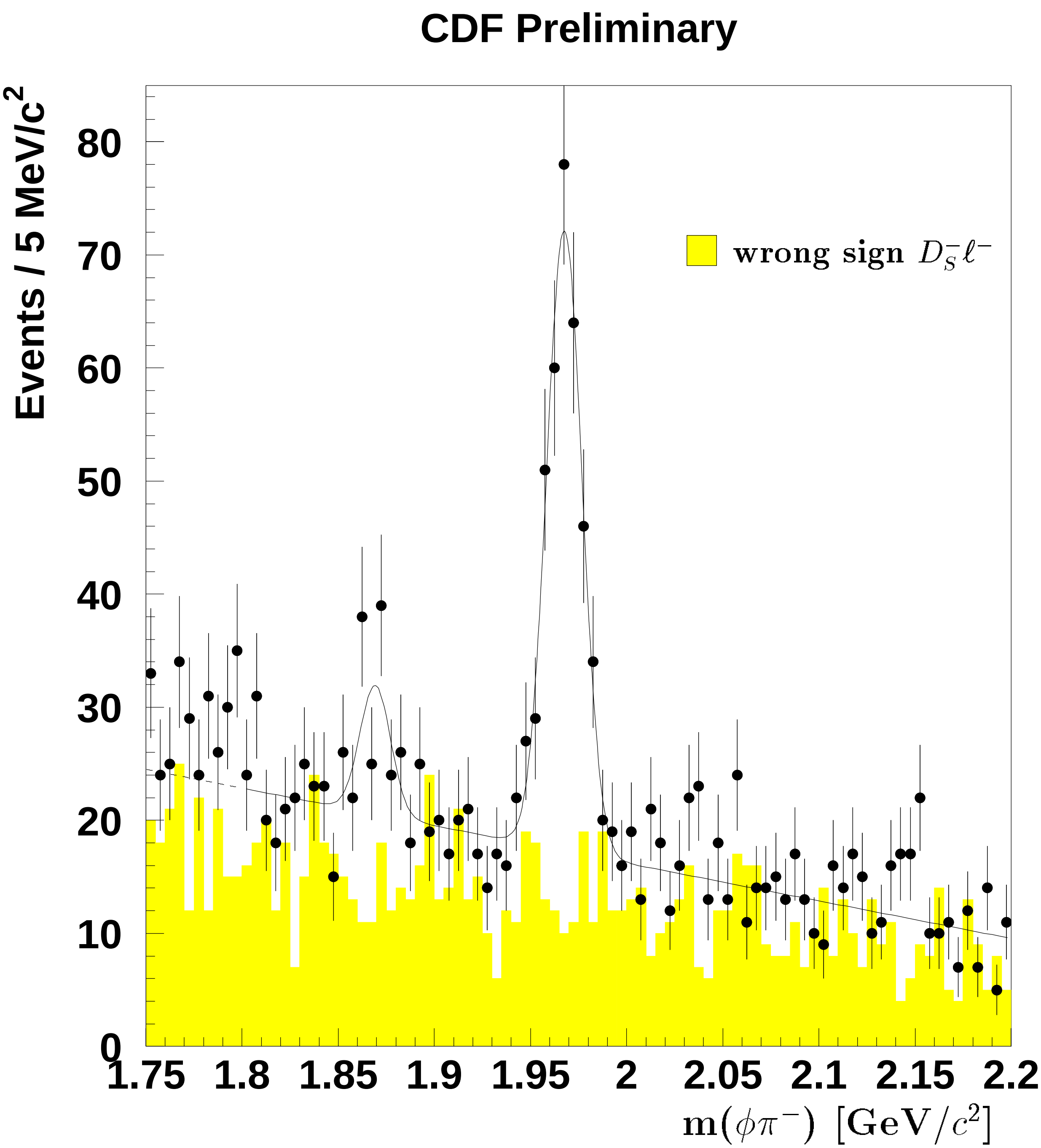

Figure 1: Invariant mass distribution of $D_s^- \to \phi\pi^-$ for right-sign $D_s^-\ell^+$ combinations with the results of the fit superimposed. The shaded histogram shows the wrong-sign distribution.

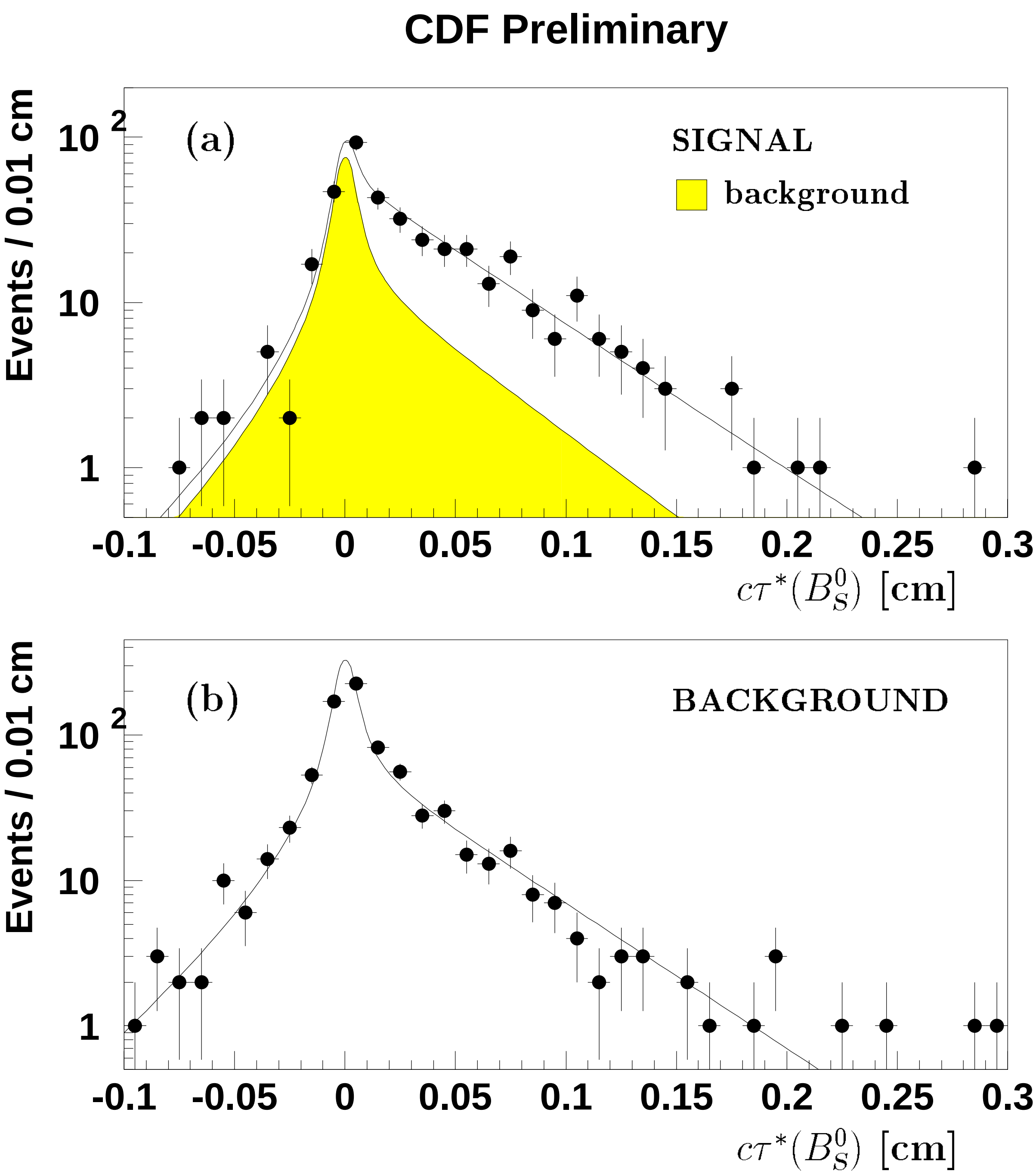

Figure 2: (a) Proper decay length distribution $c\tau^*(B_S^0)$ for the $D_S^-\ell^+$ signal sample with the result of the fit superimposed. The shaded curve represents the contribution from the combinatorial background. (b) Proper decay length distribution $c\tau^*(B_S^0)$ for the background sample with the fit result superimposed.

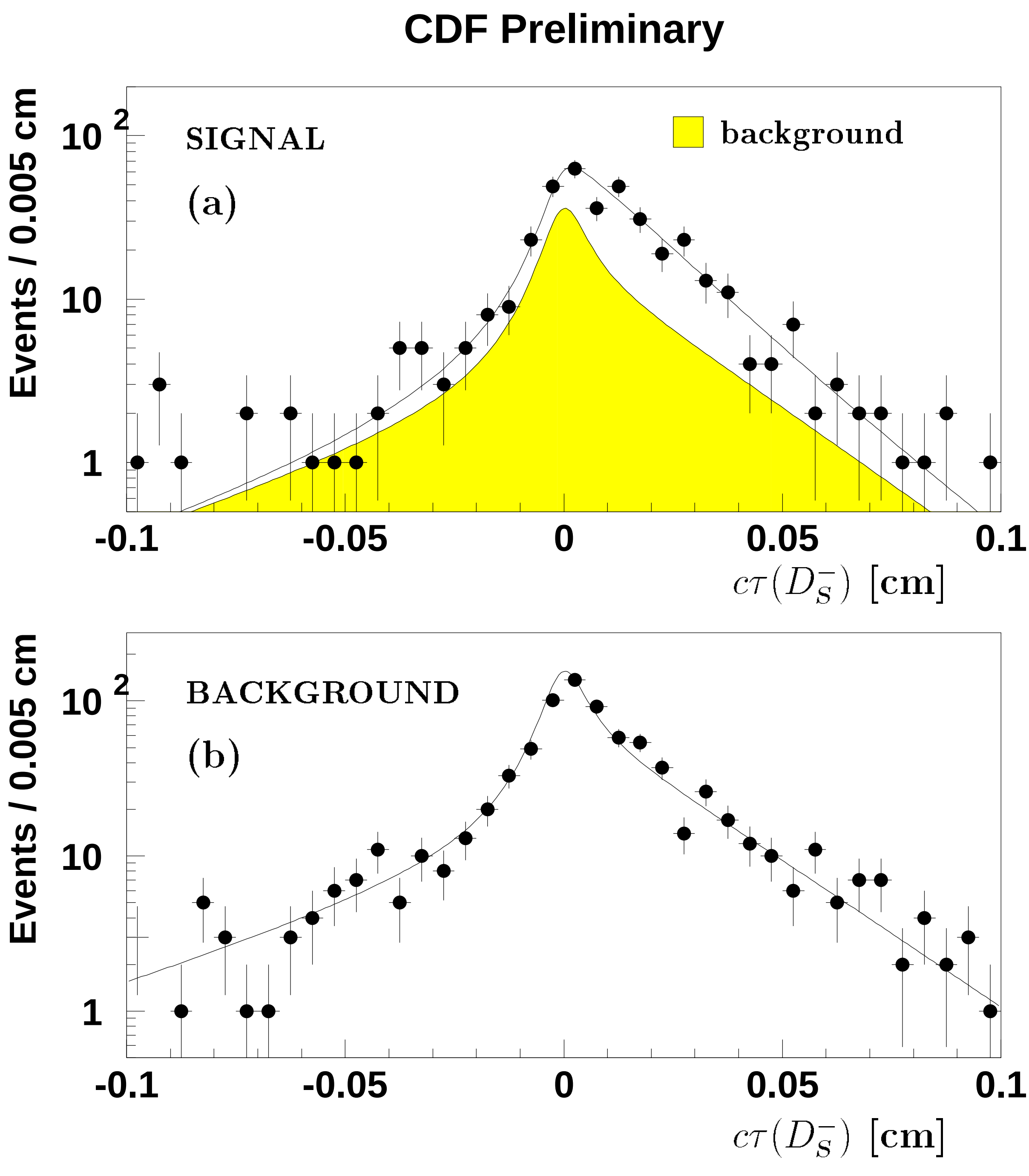

Figure 3: (a) Proper decay length distribution $c\tau$ for the D_S^- signal sample with the result of the fit superimposed. The shaded curve represents the contribution from the combinatorial background. (b) Proper decay length distribution $c\tau$ for the background sample with the fit result superimposed.